The strong interaction puzzle and nuclear physics 9

- Nuclei are held together by the "strong interaction", which, at the microscopic level, is a strongly attractive short range force between **quark** constituents of matter, mediated by the exchange of virtual particles called "**gluons**". The strong interaction theory is known as "quantum chromodynamics" or QCD.

- QCD has the property that the potential energy between a pair of quarks **increases** as their separation increases – this leads to the property of "confinement" – isolated quarks are never observed in nature, but only their bound states, eg protons, neutrons

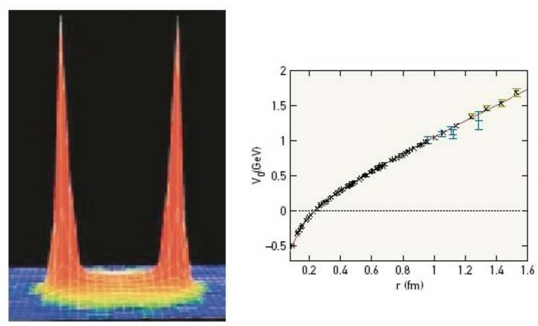
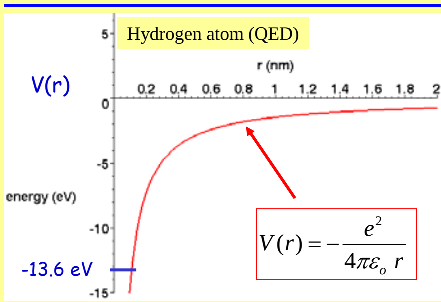
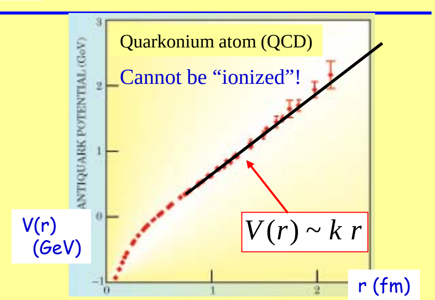


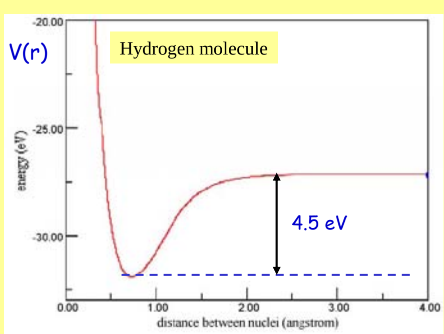
Figure 2.7. Fields of color. Lattice QCD has confirmed the existence of flux tubes between distant, static massive charges (left). The constant-thickness flux tube between the two quarks leads to a potential that rises linearly as a function of separation (right).

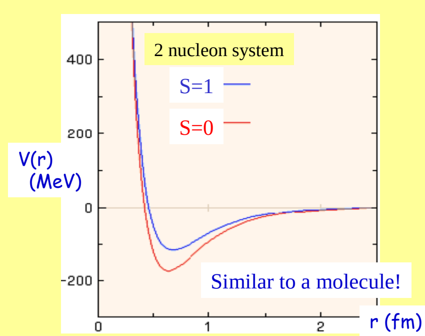
from "Opportunities in Nuclear Science", US - DOE Long Range Plan, April, 2002

Comparison: Coulomb and interquark potentials









continued... 10

• While there exists an "exact" theory of QCD, it is unfortunately too complicated to solve for the properties of its bound states, not even the basic proton and neutron, although progress is steadily being made with large scale numerical simulations

• Despite decades of effort, nobody has yet succeeded at deriving the nuclear force from QCD, so nuclei are described by phenomenological models and an effective theory, guided by experimental data.

Comment –

The nuclear force is much weaker than QCD -- after all, free protons and neutrons exist, while free quarks do not --

it must arise from QCD as a "residual force" similar to the weak binding of molecules (van der Waals force) compared to the relatively strong binding of electrons in atoms (Coulomb potential).

• Despite the lack of a "fundamental", solvable theory, nuclear models have been remarkably successful at describing the structure and properties of many stable and unstable nuclei, including an amazing range of nuclear excitation phenomena, as we will see in the lectures ahead.

Fundamental interactions in nuclei *(2 protons, 1 fm apart)* 11

1. Strong interaction (QCD) scale: 1
   - responsible for nuclear binding
   - alpha decay, nuclear fission and fusion processes

2. Electromagnetic interaction scale: 0.01
   - correction to binding energies, N>Z for heavy nuclei
   - gamma decay of excited states

3. Weak interaction scale: 0.0000001
   - nuclear beta decay
   - mirror symmetry violation

4. Gravitational interaction scale: 10^{-36}
   - forget it!

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B 592, 1 (2004) (URL: http://pdg.lbl.gov)

N BARYONS
($S = 0$, $I = 1/2$)

p, $N^+ = uud$; n, $N^0 = udd$

p

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.00727646688 \pm 0.00000000013$ u
Mass $m = 938.27203 \pm 0.00008$ MeV [a]
$|m_p - m_{\bar{p}}|/m_p < 1.0 \times 10^{-8}$, CL = 90% [b]
$|\frac{q_{\bar{p}}}{m_{\bar{p}}}|/(\frac{q_p}{m_p}) = 0.99999999991 \pm 0.00000000009$
$|q_p + q_{\bar{p}}|/e < 1.0 \times 10^{-8}$, CL = 90% [b]
$|q_p + q_e|/e < 1.0 \times 10^{-21}$ [c]
Magnetic moment $\mu = 2.792847351 \pm 0.000000028\ \mu_N$
$(\mu_p + \mu_{\bar{p}}) / \mu_p = (-2.6 \pm 2.9) \times 10^{-3}$
Electric dipole moment $d < 0.54 \times 10^{-23}$ $e$cm
Electric polarizability $\alpha = (12.0 \pm 0.6) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (1.9 \pm 0.5) \times 10^{-4}$ fm^3
Charge radius $= 0.870 \pm 0.008$ fm
Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% ($p \rightarrow$ invisible mode)
Mean life $\tau > 10^{31}$ to 10^{33} years [d] (mode dependent)

Particle Data Group – referees a compendium of credible data in nuclear and particle physics (revised annually)

n.b. age of the universe? approx. 10^{10} yr.
See http://www.astro.ucla.edu/~wright/age.html

9/13/2006

Intrinsic spin: S = ½ (fermion) *(listed as J in the table)*

important consequence: Pauli exclusion principle – no two identical fermions can occupy the same quantum state.

Intrinsic parity: π = + *(listed as P in the table)*

symmetry of the intrinsic wave function for + parity:

$$\psi(-\vec{r}) = +\ \psi(\vec{r})$$

Mass: m = 1.67 x 10^{-27} kg, or rest energy mc^2 = 938.3 MeV

lighter than the neutron – the only stable 3-quark system

- precision mass measurement: $\Delta m/m \sim 10^{-10}$!!!!

6

Precision mass measurements: Penning Trap technique[1]

3

The Nobel Prize in Physics 1989

Hans Dehmelt
University of Washington

Wolfgang Paul
Universitat Bonn

for the development of the ion trap technique

Norman F. Ramsay
Harvard University

for invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks

http://www.nobel.se/physics/laureates/1989/illpres/

[1]Also precision magnetic moment measurements, especially for the electron – more later!

Basic idea:

Ref: Brown & Gabrielse, Rev. Mod. Phys. 58, 1986 p. 233

4

Geonium theory: Physics of a single electron or ion in a Penning trap

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A single charged particle in a Penning trap is a bound system that rivals the hydrogen atom in its simplicity and provides similar opportunities to calculate and measure physical quantities at very high precision. We review the theory of this bound system, beginning with the simple first-order orbits and progressively dealing with small corrections which must be considered owing to the experimental precision that is being achieved. Much of the discussion will also be useful for experiments with more particles in the trap, and several of the mathematical techniques have a wider applicability.

- confinement in electric and magnetic fields leads to motion in **characteristic orbits**
  (orbits are quantized – hence the analogy to atomic systems)
- oscillation frequency is proportional to **(e/m)** ratio for the charged particle
- **resonant electrical signal** from exciting quantized oscillations can be detected by an external circuit
- **linewidth must be very narrow** to achieve high precision -- some tricks:
  - very stable B field (superconducting magnet)
  - carefully constructed and tuned or "compensated" electrode structure
  - cooling of electronics to liquid He temperature for low noise
- **comparison** of signals for reference and to-be-measured particle for calibration

Basic Penning Trap Configuration: 5

- uniform, axial B field (superconducting solenoid) plus quadrupole E field:

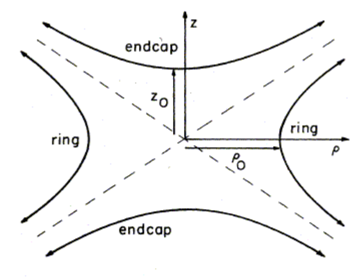
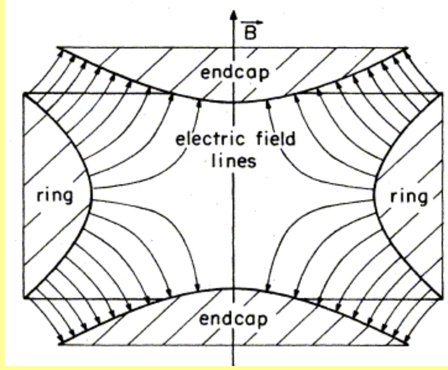


FIG. 6. Axially symmetric electrodes are used to produce a quadrupole potential of the form given by Eq. (2.2). The dashed lines represent the cones that are the asymptotes of the hyperbolas of revolution.



- particles orbit around B field at cyclotron frequency, $\omega_c \cong eB/m$; radius given by energy.
- vertical confinement due to E; axial oscillations about horizontal midplane of trap

Motion analysis: 6

- cylindrical coordinates: (ρ,ϕ,z);
- B = constant along z
- radial (ρ) and axial (z) electric field

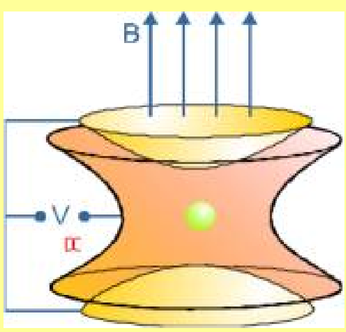
$$\vec{E} = -\vec{\nabla} V \quad with \quad V = V_o \left[\frac{z^2 - \rho^2/2}{2\,d^2}\right]$$

$$\boxed{\vec{E} = \left(\frac{V_o}{d^2}\right)\left(-\vec{z} + \tfrac{1}{2}\vec{\rho}\right)}$$

$$\text{Lorentz force:}\quad \vec{F} = q\left(\vec{E} + \vec{v}\times\vec{B}\right)$$

$$\ddot{\vec{\rho}} = \left(\frac{e}{m}\right)\left[\left(\frac{V_o}{2\,d^2}\right)\vec{\rho} + \dot{\vec{\rho}}\times\vec{B}\right]$$

$$\ddot{z} = -\left(\frac{e}{m}\right)\left(\frac{V_o}{d^2}\right) z = -\omega_z^2\, z$$



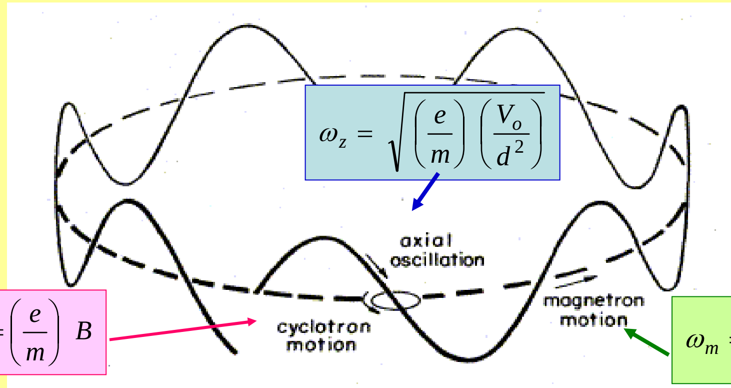
A superposition of three motions for a given particle energy near the center of the trap:

"modified cyclotron"

1. circular orbits around the magnetic field at the cyclotron frequency $\omega_c' = eB/m - \omega_m$
2. vertical oscillations (along z) at the axial frequency ω_z
3. slow circular orbits in the horizontal plane at the magnetron frequency $\omega_m = \omega_z^2 / 2\,\omega_c$

Particle Orbits: 7

Important point: energy is quantized in units of $\hbar\omega$ for the various types of particle motion. Hence, the trapped particle has an energy level structure that can be probed by emission and absorption of photons – just like an atom!



$$\omega_z = \sqrt{\left(\frac{e}{m}\right)\left(\frac{V_o}{d^2}\right)}$$

$$\omega_c = \left(\frac{e}{m}\right) B$$

$$\omega_m = \left(\frac{V_o}{2d^2 B}\right)$$

FIG. 3. Orbit of a charged particle in a Penning trap. The dashed line is the large and slow magnetron circle component of the motion. This, added to the axial oscillation, produces the guiding-center motion shown by the solid line. The total motion is given by adding the fast but small cyclotron circular motion about this moving guiding center.

Detection schemes: 8

- axial and cyclotron oscillation frequencies are proportional to (e/m).
- trapped ions absorb power when driven at a resonance frequency
- comparison of two species in the trap gives mass ratio to high accuracy without having to know the absolute B field strength to the same precision

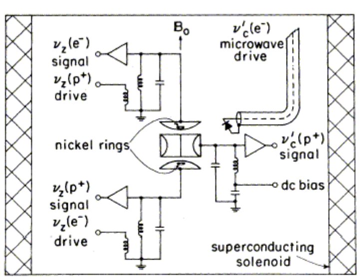


FIG. 1. Schematic of experiment. Both endcaps and the quadring have tuned preamplifiers attached to measure either ν_z or ν_c'. rf axial drives are applied to the endcap opposite the detector and microwave excitation for $\nu_c(e^-)$ radiates from a Schottky multiplier diode.

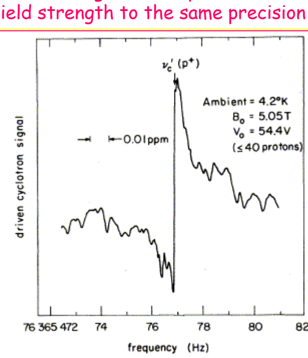


FIG. 3. Proton cyclotron resonance. The drive phase has been adjusted to approximately produce a dispersion curve during synchronous detection. The linewidth is limited primarily by observation time.

Examples from early paper on proton/electron mass ratio: Phys. Rev. Lett. 47, 395 (1981)

-- precision was already so high that there is a correction required to account for the number of particles in the trap! ($\Delta m/m$ correction to m_p/m_e = -1.2×10^{-10}/ particle; for one species, -2.2×10^{-7})

Typical parameter values

TABLE II. Trapping parameters for a proton. The numerical values are for one version of the electron-proton mass ratio experiment (Van Dyck and Schwinberg, 1981). The measured axial frequency is only approximately related to the trap potential and trap size of Eq. (2.7) because of electrostatic effects discussed in Sec. IX.

External parameters		
Trap potential	$V_0 = 53.10$ V	
Trap sizes	$d = z_0 = \rho_0/\sqrt{2} = 0.112$ cm	
Field strength	$B = 50.50$ kG	
Measured eigenfrequencies and energy-level spacings		
Cyclotron	$\nu_c' = 76.34$ MHz	$\hbar\omega_c' = 3.157 \times 10^{-7}$ eV
Axial	$\nu_z = 10.06$ MHz	$\hbar\omega_z = 4.160 \times 10^{-8}$ eV
Magnetron	$\nu_m = 662.8$ kHz	$\hbar\omega_m = 2.741 \times 10^{-9}$ eV
Estimated damping widths (Secs. III.A and III.E)		
Cyclotron	$\gamma_c/2\pi \approx 10^{-3}$ Hz (coupling to external circuit)	
Axial	$\gamma_z/2\pi \approx 10^{-3}$ Hz (coupling to external circuit)	
Magnetron	$\gamma_m \approx$ unmeasurably small	

Rev. Mod. Phys., Vol. 58, No. 1, January 1986

N.B. How to access electronic journals: http://umanitoba.ca/libraries/online/ejournals/

VOLUME 92, NUMBER 19 PHYSICAL REVIEW LETTERS week ending 14 MAY 2004

Precise Mass Measurement of ^{68}Se, a Waiting-Point Nuclide along the *rp* Process

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(Received 26 November 2003; published 13 May 2004)

Mass measurements of ^{68}**Ge**, ^{68}**As**, and ^{68}**Se** have been obtained with the Canadian Penning Trap mass spectrometer. The results determine the mass excess of ^{68}**Se** as **−54232(19) keV**, the first measurement with a precision and reliability sufficient to address the light-curve and energy output of x-ray bursts as well as the abundances of the elements synthesized. Under typical conditions used for modeling x-ray bursts, ^{68}**Se** is found to cause a significant delay in the *rp* process nucleosynthesis.

$\boxed{\delta M / M \approx 2 \times 10^{-7}}$

Manitoba connection: Sharma, Clark, Vaz, Wang ...

- Dr. Sharma is the leader of the Canadian Penning Trap Mass Spectrometer (CPTMS) group, currently making mass measurements of selected unstable nuclei which play an important role in determining reaction rates important in stellar nucleosynthesis.

- Experiments are carried out at Argonne National Lab's "ATLAS" facility: http://www.phy.anl.gov/atlas/index.html

VOLUME 82, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1999

Precision Mass Spectroscopy of the Antiproton and Proton Using Simultaneously Trapped Particles

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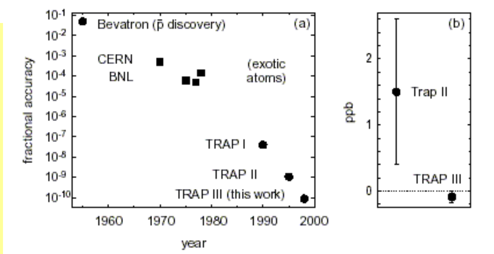
(Received 10 November 1998)

This last of a series of three measurements improves the comparison of antiproton ($\bar{p}$) and proton (p) by almost a factor of 10^6 over earlier exotic atom measurements, and is the most precise *CPT* test with baryons by a similar large factor. Measuring the cyclotron frequencies of a simultaneously trapped $\bar{p}$ and H^- ion establishes that the ratio of q/m for $\bar{p}$ and p is $-0.99999999991 \pm 0.00000000009$, more than 10 times the accuracy over our previous measurement. This 9×10^{-11} comparison makes the first use of simultaneously trapped particles for sub-ppb spectroscopy. [S0031-9007(99)08869-9]

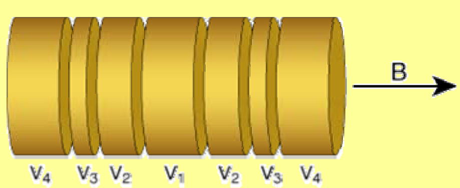


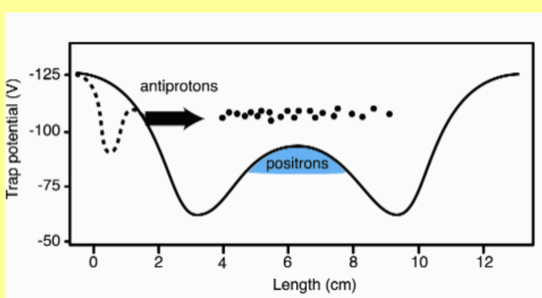
State of the art today:

precise proton-antiproton mass comparison to test matter/antimatter symmetry.

Antihydrogen experiments at CERN:

main goal is **trapping** for both antiprotons and positrons to encourage atom formation – use a **cylindrical** Penning trap:





potential minimum traps antiprotons – maximum traps positrons...

Big news: Sept. 2002

website:
http://athena.web.cern.ch/athena/

13

advance online publication

Production and detection of cold antihydrogen atoms

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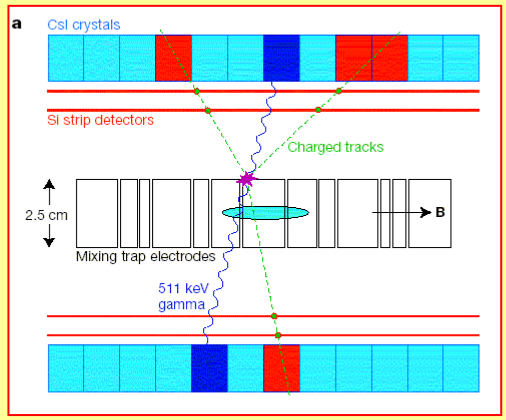
nature

This advance online publication (AOP) *Nature* paper should be cited as "Author(s) *Nature* advance online publication, 18 September 2002 (doi:10.1038/nature01096)". Once the print version (identical to the AOP) is published, the citation becomes "Author(s) *Nature* volume, page (year): advance online publication, 18 September 2002 (doi:10.1038/nature01096)".

Figure 1 Central part of the ATHENA apparatus and trapping potential. **a**, Schematic diagram, in axial section, of the ATHENA mixing trap and antihydrogen detector. The cylindrical electrodes and the position of the positron cloud (blue ellipse) are shown. A typical antihydrogen annihilation into three charged pions and two back-to-back 511-keV photons is also shown. The arrow indicates the direction of the magnetic field. The detector active volume is 16 cm long and has inner and outer diameters of 7.5 cm and 14 cm, respectively



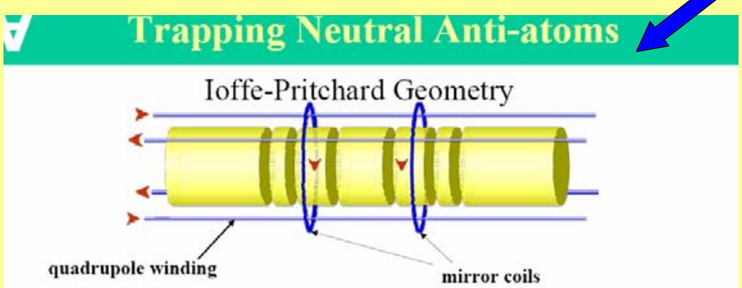
These first results showed that antihydrogen atoms were indeed produced in significant quantities, but after that, the neutral atoms just floated to the walls of the trap, where they annihilated with normal atoms and their decay products were observed in a sensitive detector.

The next step…

New collaboration: "Alpha" , approved
For running at CERN in 2006. Dr. Gwinner
Is a member of the Alpha collaboration!

http://alpha.web.cern.ch/alpha/

The next step towards a long term goal of testing the spectroscopy of antihydrogen requires that the neutral anti-atoms can be trapped and studied using normal atomic physics techniques.



$$U = -\vec{\mu} \cdot \vec{B}$$

Magnetic bottle idea – the magnetic moment of the anti-hydrogen atom interacts with an imposed magnetic field. Atoms with their spin in the right direction are trapped by the magnetic "walls" (not enough energy to overcome the magnetic force), while those in the other direction can escape. The magnetic "bottle" has to be created in the same region of space as the Penning trap which brings the components together, without disturbing the functioning of the main Penning trap. A magnetic quadrupole field is the simplest one to try, but the alpha collaboration has already realized that a higher multipolarity field (e.g. octupole will probably be needed to make this work in practice.)